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# Confronting challenges of managing degraded lake ecosystems in the Anthropocene, exemplified from the Yangtze River Basin in China

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ABSTRACT

Freshwater lake ecosystems have supported livelihoods for millennia. Yet, most lakes worldwide today are suffering severe degradation in response to anthropogenic pressures. Scientists and managers are facing pressing challenges to define safe operating space for successful lake management into the future. Achieving these goals requires a clear understanding of nonlinear trajectories of ecosystems response to changes in multiple interacting drivers at multi-decadal scales. Based on a synthesis and analysis of published paleo-environmental records, this paper shows that many lakes in the Middle and Lower Yangtze River Basin (MLYB) have undergone abrupt ecological shifts during the 1950s–1980s. The causes for these significant changes were multiple accumulating drivers acting together through time including climate change, land reclamation, agricultural intensification, and industrialization. This paper also explored the potential of defining the Anthropocene baseline for proper restoration and management in the MYLB based on paleo-environmental records. That is, we reveal that a return to the pre-1900s historical condition is no longer possible for many degraded lakes due to both socioeconomic and ecological constraints. For some severely degraded lakes with high sedimentation rates, restoration to the 1970s and 1980s levels within the historical range of variability might be more realistic, though constrained by socioeconomic limitations on reducing anthropogenic drivers. Management actions can still guide other lakes with low or moderate levels of sedimentation toward their pre-1900s conditions. This analysis is the first of its kind in illustrating within the MYLB that long-term paleo-environmental records can have useful applications in identifying the restoration targets in degraded aquatic ecosystems. It also suggests a pathway for potentially improving the resilience of such social-ecological systems toward sustainability.

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## 1. Introduction

The extent and scale of human-biosphere interactions in recent centuries are unprecedented, altering the dynamics of ecosystems throughout the world (Johnson et al., 2017). Freshwater lake ecosystems are among the most altered and damaged on the planet while supporting the food security and livelihoods for millions of people worldwide (Beklioğlu et al., 2016). Increasingly, scientists and managers encounter previously unseen configuration of species in many lake ecosystems (Dubois et al., 2017). Land degradation, declining water quality, overharvesting, climate change, and other human-induced drivers have resulted in major alterations to the species composition and trophic structure of freshwater ecosystems. Extensive physical, chemical and biotic transformations in lake ecosystems have been observed in many locations around the world (Dubois et al., 2017). Observational, experimental and modeling studies suggest that many shallow lakes have experienced transitions from clear, macrophyte-dominated state to turbid, phytoplankton-dominated states, with the substantial reorganization of species and assemblages of aquatic communities (Scheffer and Jeppesen, 2007). These ecological shifts are important for the management and restoration of lake ecosystems because they often result in profound changes in ecosystem services, biodiversity, and esthetic values. They are also hard to predict and avoid, and are often costly, difficult, or even impossible to reverse (Scheffer et al., 2001).

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Scientists and managers have increasingly accepted the impossibility of returning highly degraded lake ecosystem to their past configuration. The recent Anthropocene baseline concept proposed by Kopt and others (Kopf et al., 2015) acknowledges the conservation value of the remnants of historical ecosystems, but also emphasize that certain ecosystems have arrived at a new point of reference due to the accelerating human impacts in the Anthropocene. Managers and policymakers are facing pressing challenges to identify these reference conditions, maintain the ecosystem functions that are crucial for sustaining lake ecosystems, and to secure the ecosystem services that highly altered lake ecosystems can provide to people in the future (Hilt et al., 2017). Central to this endeavor is an improved understanding of long-term dynamics of lake ecosystems driven by both slow (i.e. climate change, catchment erosion) and fast (i.e. rapid socioeconomic development) drivers over various timescales, in order to define regional safe operating spaces (keep lake ecosystems within acceptable levels of boundaries) for future sustainability (Dearing et al., 2014; Scheffer et al., 2015).

The Middle and Lower Yangtze River Basin (MLYB) constitutes one of the largest groups of freshwater shallow lakes in the world (Fig. 1) (Wang, 1998). The catchment covers approximately 785,000 km$^2$, with more than 5900 (in number) or 15,000 km$^2$ freshwater lakes, ponds and reservoirs, accounting for nearly 25% of the freshwater lake area in East Asia (Wang et al., 2014). Freshwater lakes in MLYB provide essential ecosystem services (e.g. food, water, aesthetic and spiritual values) to sustain agricultural production and socioeconomic development in the region with nearly half a billion population. As a harbinger of China's environmental change, shallow lakes in the MLYB have experienced serious degradation (Fig. 2) (Ding et al., 2015; Fang et al., 2006). Human has modified lake ecosystems in this region for millennia, but recent industrialization and urbanization have resulted in an exponential rise in the anthropogenic modification and use of lake resources (Ellis and Wang, 1997; Yang and Lu, 2014). A recent survey showed that more than 90% of the shallow lakes in these regions are experiencing eutrophy and hyper-eutrophy, and more than 1000 lakes (>1 km$^2$) with a total area of 13,000 km$^2$ disappeared in the middle and lower Yangtze River Basin during the last five decades (Wang, 2015). Lake deterioration has led to the loss of biodiversity, damage to ecological services, as well as increased environmental disasters, such as the catastrophic Yangtze floods in 1998 and Taihu water crisis in 2007 (Qu et al., 2014; Wang et al., 2015).

China has made tremendous efforts to restore and manage the highly degraded lake ecosystems over the recent decade (Le et al., 2010). Billions of dollars are dedicated to lake ecosystem restoration via environmental protection actions (e.g. establishment of wastewater treatment plants, shutdown of heavily polluting factories, closure of aquaculture fisheries) (Wang, 2015; Zhou et al., 2017). Nevertheless, the extent to which China can protect and repair these degraded lake ecosystems, at what cost, and over what timeframe represent daunting challenges. Many current restoration and management practices inadvertently simplify and rescale these complex issues into a subsystem that is entirely ecological, and focusing on the symptom rather than the deep fundamental causes (Zhang et al., 2016). Lake management strategies ignoring these complex interactions frequently failed to achieve their anticipated outcomes and many lake improvements are sometimes short-lived (Crépin et al., 2012). For example, the cost of cleanup efforts in China's third largest body of freshwater, Taihu Lake, since 2007 has exceeded US $16 billion, yet massive blooms of algae and cyanobacteria still reoccur almost every year, threatening the water supply to 30 million people. Shallow lakes in this region will likely become extremely vulnerable to future changes in climate and other anthropogenic pressures (Qin et al., 2013).

Although progress has advanced considerably about changes in lake ecosystem in the Yangtze River Basin, most of studies mainly focus on recent "symptoms" of the problems rather than their deep historical causes (Wang, 2015). The extent and spatiotemporal variability of lake ecosystems change, in particular, is still poorly

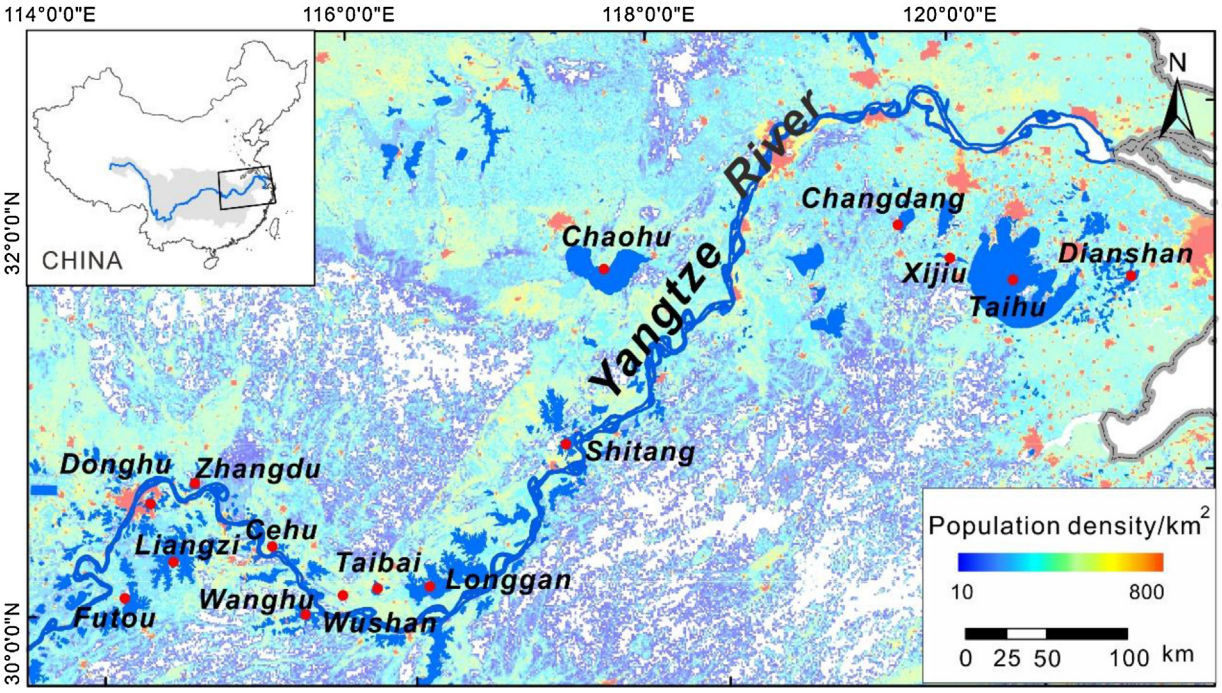


**Fig. 1.** Maps showing the 15 studied lakes (red dots) within the distribution of shallow lakes across the Middle and Lower Yangtze River Basin (MLYB). The color gradient represents the population density per square kilometers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Fig. 2.** Examples of degraded lake environment in the MLYB: (a) Turbid water covered densely by green alga in Taihu Lake; (b) Tourist waste and domestic garbage were dropped on the shore of Taibai Lake; (c) Fishing boat laid up at the Longgan lake, in which fisher man intensively used to collect fish and snails; (d) Floating aquatic plants cover most of the surface area in Yangfang lake. Photos taken in June 2017 by Yanjie, Zhao (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

known. This paper analyzes existing paleoenvironmental records from the published literature for the MLYB to determine how shallow lakes have changed over the past century. In doing so, it also raises challenges for sustainable management of heavily degraded aquatic systems. Firstly, by reviewing and synthesizing the large body of published paleoecological records, we document the abrupt shift of lake ecosystems from the MLYB over the past century. Secondly, from this analysis, we identify how multiple pressures have changed and acted on lake ecosystems. Third, we explore the potential of defining the anthropogenic baseline in this region based on the long-term paleoenvironmental records, in order to assess proper and realistic restoration target. Finally, we provide suggestions and recommendations for sustainable lake management and restorations.

## 2. Material and methods

### 2.1. Paleoenvironmental records

We compiled published records of diatom, cladoceran, chironomid, and pollen from lake sediment in the MLYB for synthesis and identification of abrupt changes in the conditions of lake ecosystems. We also compiled data on trace metals and sedimentation rates for assessing the potential restoration baseline in the Anthropocene. In other words, the time period when human impacts on lake ecosystems accelerated exponentially. These paleo-records have been published and interpreted in details (Table 1). In these studies, sediment records at each site are derived from sediment cores taken from the deepest sections of each lake, and cores were subsampled at a resolution of 0.5–1.0 cm, freeze-dried, and prepared for subsequent analysis. Diatom, cladoceran and pollen analysis followed the standard procedures (Battarbee et al., 2001; Fægri and Iversen, 1989; Szeroczyńska, 2007). Trace metal elements, including Aluminum (Al), Iron (Fe), Lithium (Li), Potassium (K), Magnesium(Mg), Chromium (Cr), Copper (Cu), Zinc (Zn), and Strontium (Sr) were analyzed using an Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). All sediment core samples were dated using $^{210}$Pb and $^{137}$Cs by non-destructive gamma spectrometry. Sedimentation rate (SR; g cm$^{-2}$ year$^{-1}$) in each core were derived from $^{210}$Pb/$^{137}$Cs dating (Xu et al., 2017a).

### 2.2. Social and economic records

The China Statistical Yearbook and the China Compendium of Statistics (1949–2008), published by the National Bureau of Statistics of China (http://www.stats.gov.cn/, accessed in October 1st 2018), provided data for the gross domestic product (GDP). The China Fishery Statistical Yearbook (year) provided data for the fresh aquaculture yield (Fisheries Bureau of Ministry of Agriculture, 2017). The Earth Policy Institute data center (http://www.earthpolicy.org/data_center/, accessed in October 1st 2018) contained data for usages of fertilizer for China. Regional climate model generated the annual temperature and precipitation in east China (Jian et al., 2005). The cropland area and population data are from the study of Miao et al., (2016). The climate, cropland area and popultion records used in this study are all covered the last 100 years. The reservoir data are from the publication of Yang et., al (Yang and Lu, 2014), which compile all the reservoir build since 1950 in China. The social and economic data in the Changdang Lake catchment were collected from the statistic yearbook, historical document, and local county gazetteers from Jintan County (Meng, 1993).

### 2.3. Statistical analysis

#### 2.3.1. Detections of abrupt shift

For most of the lakes examined here (except Futou and Wushan Lake), firstly, we applied a standardized principal component analysis (PCA) to extract major components of the diatom,

**Table 1**
Summary of paleo-environment data used in this study (SAR, sedimentary accumulation rate).

| Lake Name | Location | | Lake size (km2) | Sediment Cores | Year (AD) | Records | Source |
|---|---|---|---|---|---|---|---|
| Dianshan | N 31°08' | E 120°57' | 63.7 | DS3 | 1896–2010 | Trace metal, (SAR) | Li et al. (2013) |
| Taihu | N 30°14' | E 119°44' | 2338 | DLS, MS | 1800–2005 | Diatom, SAR, trace metal | Shen et al. (2007), Dong et al. (2008) |
| Xijiu | N 31°23' | E 119°42' | 12.4 | XJ1, XJ5 | 1890–2004 | SAR, trace metal | Wu et al. (2010a) |
| Changdang | N 31°36' | E 119°33' | 89 | CD1, C1, | 1900–2017 | Diatom, pollen, cladoceran, trace metal | Ge et al. (2018) |
| Chaohu | N 31°34' | E 117°34' | 769.6 | C2007 | 1500–2006 | Diatom, SAR, trace metal | Chen et al. (2011); Du et al. (2012) |
| Longgan | N 29°58' | E 115°48' | 316.2 | LS1, LGL1 | 1896–2007 | Diatom, SAR, trace metal | Wu et al. (2010b), Zhang et al. (2012) |
| Taibai | N 29°58' | E 115°48' | 26 | TB,TN | 1840–2007 | Diatom, chironomid, trace metal | Yang et al. (2008), Liu et al. (2012), Zhang et al. (2012) |
| Wushan | N 29°55' | E 115°34' | 16.1 | WS | 1860–2007 | Diatom, Chironomid | Zhang et al. (2010) |
| Wanghu | N 29°53' | E 115°22' | 35.2 | WS | 1860–2010 | SAR, trace metal | Shi et al. (2013) |
| Cehu | N 30°15' | E 115°09' | 11.8 | CH | 1850–2011 | SAR | Xu et al. (2017a, 2017b) |
| Zhangdu | N 30°39' | E 114°44' | 42.3 | ZD | 1863–2011 | Diatom, cladoceran,trace metal, SAR | Dong et al. (2016), Giri et al. (2016), Zhang et al. (2013) |
| Liangzi | N 30°12' | E 114°30' | 304.3 | LZ | 1850–2011 | Diatom, cladoceran,trace metal, SAR | Zhang et al. (2014), Dong et al. (2016), Giri et al. (2016) |
| Donghu | N 30°33' | E 114°24' | 33.7 | DH2 | 1900–2003 | SAR,trace metal | Yang et al. (2005) |
| Futou | N 30°01′ | E 114°12' | 126 | FT | 1815–2014 | Trace metal,diatom, SAR | Zeng et al. (2018) |

cladoceran, chironomid, and aquatic pollen assemblages. PCA is a dimensionality-reduction technique that is often used to transform a high-dimensional dataset into a smaller-dimensional subspace (Seddon et al., 2014). Then we applied the sequential *t*-test Analysis of Regime-Shifts algorithm (STARS) (Rodionov, 2006) to detect abrupt changes based on the first principal component (PCA1) of different aquatic assemblages. We use a cut-off length of 20 years in each analysis and choose the largest regime shift index (RSI) value, which are more statistically significant ($p < 0.05$). For Futou and Wushan lakes, the timing of aquatic shift was estimated based on the studies of Zeng et al., (2018), and Zhang et al., (2010). We also applied general additive model (GAM) (Simpsona and Anderson, 2009) in order to examine temporal trends and investigate the nonlinear relationships between aquatic community dynamics and external pressures, using Changdang Lake here as an example, which is a typical shallow lake (mean depth, 1.2 m) with moderate size (89 $km^2$) in this region and has experienced extensive modification over the past century.

*2.3.2. Baseline calculation*

For the sedimentation, we normalized (0–1) all the raw sediment accumulation rates so that trends could be easily compared and aggregated. Sedimentation rate ($g.cm^{-2}\,year^{-1}$) in each lake were derived from $^{210}Pb/^{137}Cs$ dating and has been summarized in details in Xu et al., (2017a,Xu et al., 2017b. The formula used for scaling the data series (x1:xn) to (0:1) is x1 − (min x1:xn)/[(max x1:xn) − (min x1:xn)], where min and max are minimum and maximum values within the data range. Based on the normalized data, we calculate the average value every ten years in order to get the general temporal change. Then we divided the value of accumulation rate into three categories: low (value <0.3), moderate (0.3 ≤ value <0.6), and high (0.6 ≤ value).

For the heavy metal pollution, we calculated the factor (mainly based on Cu, Pb, and Zn) in each lake to illustrate the degree of sediment contamination. For each lake, we calculate the average enrichment factor every five years in order to get the general temporal change. Then we divided the value of enrichment factor into three categories of contamination: low (enrichment factor <1), moderate (1≤ enrichment factor <3), and high (3 ≤ enrichment factor).

## 3. Results and discussion

### 3.1. Abrupt ecological shifts

Dramatic shifts in structure and function of lake ecosystems over the last century are of major concern to modern society (Spears et al., 2017). Regime shifts are defined as large, abrupt, and persistent changes in the structure and function of ecosystems (Scheffer et al., 2001). Though researchers have proposed and supported underlying mechanisms of such shifts with different conceptual frameworks and theories (Scheffer and Carpenter, 2003), linking observed abrupt changes in the field to the mathematical theory of complex systems remains a challenging endeavour (Capon et al., 2015), making predictions of such shifts and subsequent restoration measures challenging (Hughes et al., 2013). Others take a more pragmatic way to define the regime shift based on empirical evidence rather than on the theory of catastrophic, and argue that emphasis on this theoretical aspect often hinders progress in considering abrupt changes in ecosystem-based management (Conversi et al., 2015). In this paper, we also include regime-like change as a regime shift even without evidence of multiple alternative stable states, as it is more practical for ecosystems management purposes and can be used for both benthic and pelagic regime shifts, even where the link with the mathematical theory is not yet fully established (Möllmann et al., 2015).

In the MLYB, many shallow lake ecosystems exhibited abrupt shifts in aquatic species and assemblages over the past century. Aquatic communities from different trophic level across the lake ecosystem food web all showed clear shift and reorganization

during these periods. Most of the identified ecological shifts occurred during the 1950–1980 s (Fig. 3), yet with considerable spatial and temporal differences. For instance, in Taibai, Wushan, and Zhangdu lakes, clear shifts occurred around the 1950s, when the diatom communities showed a substantial decrease in the relative abundance of epiphytic species and increase in the planktonic species (Yang et al., 2008; Zhang et al., 2013). In Chaohu and Taihu Lake, these shifts occurred around the 1970s with the pronounced increase in eutrophic planktonic diatoms (Chen et al., 2011; Dong et al., 2008). Chironomid and cladoceran microfossils in many lakes also showed a significant change in both concentration and assemblage diversity. For instance, the abundance of littoral cladoceran species increased significantly to become dominant from the late 1960s at Zhangdu and Liangzi Lak (Kattel et al., 2016). Pollen records also reveal that macrophyte community transformed from emergent-type dominant species to floating-type dominant species in Changdang Lake in the late1980s.

Increasing shifts in key components of lake ecosystems are symptomatic of the continuous decline of ecosystem resilience. Lake ecosystems comprise multiple communities and complex biotic interactions, and show strong temporal asynchrony between key species or functional groups within multiple trophic levels when facing disturbance(O'Gorman and Emmerson, 2009). As pressure increases, certain communities (i.e. diatoms) respond quickly and show small-scale shift in composition and structure with important consequence for lake functioning and stability. This response can partly explain why the results show that different aquatic communities in the same lake shift at slightly different periods. For instance, a clear shift in diatom community occurred around the 1960s in Taibai Lake, while cladoceran communities did not show big change until the mid-1970s (Fig. 3). Others also argued that the ecosystems level shifts from one state to another might be gradual or even more protracted (Hughes et al., 2013). Increasing anthropogenic pressures, such as overfishing, nutrient input, habitat modification, and climate change together have created a more simplified freshwater aquatic ecosystem with lower resilience, which can rapidly respond to external influences in unpredictable ways.

### 3.2. Multiple stressors of change in lake ecosystems

Lake degradation might result from complex interactions of multiple stressors at different spatial and temporal scales.

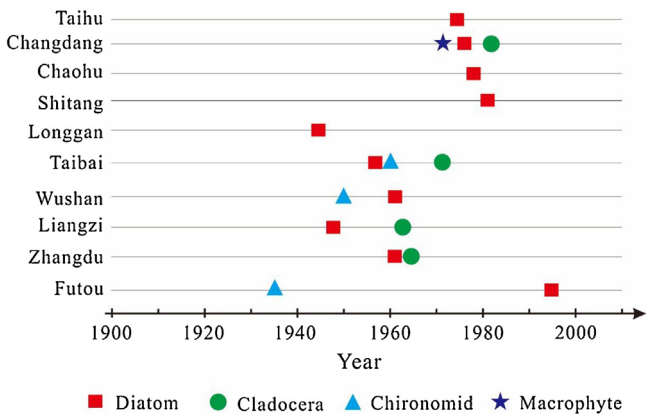


**Fig. 3.** The timing of the abrupt shifts in different aquatic communities (diatom, cladocera, chironomid, and macrophyte) in the shallow lakes in the MLYB over the last century. Breakpoints were detected based on the first principal components of the aquatic assemblages from paleoecological construction. For more details, please refer to the supplementary information.

Understanding and managing multiple stressors and their combined impact on lakes have great relevance for lake management and restoration. In general, stressors can be categorized into press-type (gradually increasing over time) and pulse-type (short-term and sharp) (Collins et al., 2011). Press-type pressures gradually undermine ecosystem resilience (i.e. nutrient loading, increasing temperature), whereas the pulse-type pressures (i.e. dam construction or flooding event) might give the final impulse for abrupt ecosystem change (Collins et al., 2011). Besides these direct stressors, other indirect drivers also have severe impact on lake ecosystems. For instance, new technology, demographic change, the opening of markets, could all influence the magnitude of direct drivers (Hicks et al., 2016). The consequence of multiple drivers acting on lake ecosystems can be different depending on certain circumstances. In theory, if nutrient loading has effect x on a lake ecosystem and climate change has effect y, the climate change and nutrient loading together might have an effect that is x + y (additive), greater than x + y (synergistic), or less than x + y (Folt et al., 1999). However, in reality, the situation is far more complex. An urgent need exists to understand whether the ecosystem response to multiple stressors is simply additive, or involves synergistic or antagonistic effects. However, current research focuses on understanding and managing multiple drivers and evidence for their combined impact is still far few.

Lakes in the MLYB are subject to a wide variety of anthropogenic influences that have degraded their economic, recreational and spiritual value. Nutrient loading is one of the major drivers that cause lake ecosystem degradation (Qin et al., 2013; Wang et al., 2015). Wastewater discharges from agriculture, industry, animal husbandry and aquaculture threaten lake ecosystems directly. For instance, fertilizer usage in China has increased from 1 million tons in 1960 to more than 53 million tons in 2012 (Fig. 4). The freshwater aquaculture yield has increased more than 25 folds during the last 30 years, and lake and pond yields accounted for over 70% of the total inland aquaculture (Cai et al., 2013). For instance, in the Futou Lake, more than 70% of its water area has been used for aquaculture, and nearly 930 tons of total phosphorus and 2800 tons of total nitrogen generated from aquaculture has been discharged into the lake each year (Zeng et al., 2018).

The hydrological modification is another big stressor that has caused the lake ecosystem degradation in the MYLB. More than 50,000 dams and reservoirs were built in the Yangtze floodplain to meet the demand for energy, irrigation and flooding mitigation since the 1950s (Yang et al., 2011). These widespread river regulations have disrupted the downstream flows, altering nutrient and sedimentation transport, and changing lake water levels. Dam construction is a major driver for aquatic community reorganization and shifts in many shallow lakes in the MLYB. For instance, long-term paleoecological records from the studies of Kong et al., (2016) and Zhao et al., (2016) indicate that the significant zooplankton and phytoplankton species shift after dams appeared at Chaohu and Taibai Lakes.

Though anthropogenic activities played a key role in lake degradation in LYB over the past several decades, climate change superimposes on these stressors and exacerbate the condition further. The annual mean temperature in this region increased 1.52 °C during 1909–2010 (Cao et al., 2013). Increasing temperature has exacerbated the symptoms of eutrophication, through its impact on algal productivity, oxygen concentrations in water columns, nutrient recycling and increased planktivory (Baig et al., 2017; Jeppesen et al., 2014). Increasingly, frequent extreme events also have big impacts on lake ecosystems. For instance, previous research revealed that typhoons are an important driver of biogeochemical and water quality perturbations at the ecosystem-level in the hypertrophic Taihu lake, and trends determined from historical in situ data indicated higher frequencies and

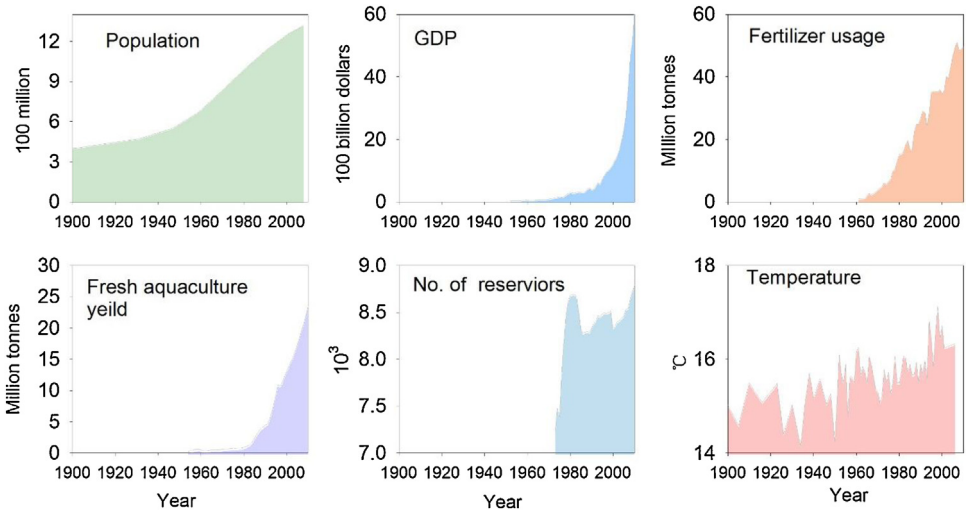


**Fig. 4.** Multiple socioeconomic accumulating drivers in China since 1900. The magnitude of drivers increased significantly over time, especially during the last 50 years. For detailed data resource and description, please see supplementary information.

intensities of blooms in "cyclone years" (Zhu et al., 2014). Given the current predictions of rapid socio-economic development (annual GDP growth rate around 7% (Li et al., 2017) and the growing threat of climate change (Deng et al., 2017), challenges to restore and manage the highly degraded lakes in this region are great.

Temporal co-occurrence of multiple escalating drivers over the last century (Fig. 4) caused the reduced resilience and ecological shift in the MLYB. In general, the land reclamation from the 1950s, dam construction from the 1960–1970 s, massive fertilizer usage from the early 1980s, intensive aquaculture from the middle 1980s, and industrialization and urbanization since the late 1980s, have accumulated and affected the lake ecosystems. These long-term complex interactions between multiple drivers and lake ecosystems can result in different press-response relationships. Taking Changdang Lake as an example, the general additive model (GAM) results showed that the aquatic ecosystem responds to external drivers (population, GDP/capita, aquaculture yield, and Crop yield) in a nonlinear way, whereas the response to climate drivers was linearly (Fig. 5). Altogether, these multiple drivers acting together with increasing internal positive feedbacks have caused severe lake degradation over time.

### 3.3. Anthropocene baselines for lake restoration

As lake ecosystems continue to decline and reconfigure in the near future, the extent to which managers can repair these degraded lakes should be debated and addressed. The historical reference condition/baseline (a point of reference in the absence of significant human activity) is the conceptual benchmark and guidelines for restoration and management in many degraded freshwater ecosystems (Battarbee and Bennion, 2011). For instance, Dong et al. (2016) explored the historical reference conditions by examining the paleo-ecological records in the East Yangtze floodplain, and established the chemical reference condition ($50ug^{-1}$) based on diatom communities around the 1800s. Others argued that the historical reference baseline concept takes a static view, however, and failed to account for aspects of the ecosystem that have been irreversibly altered from past conditions

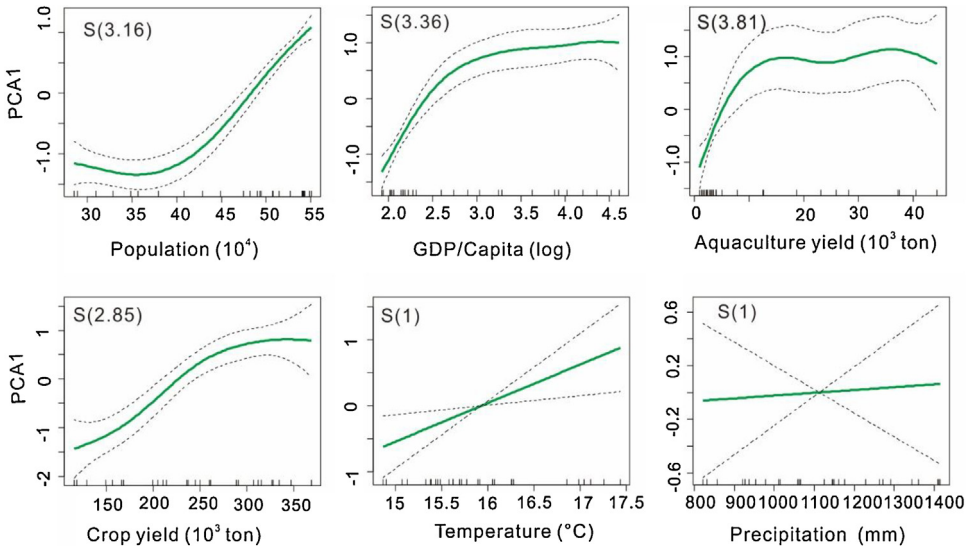


**Fig. 5.** Fitted smooth function between lake ecosystem change (macrophyte PC1 scores) and multiple external drivers from a general additive model (GAM) in Changdang Lake. Two dotted lines mark the 95% uncertainty interval of the fitted function. On the x-axis, ticks show the distribution of observed values for the two variables. The number in parenthesis is the effective degrees of freedom (edf) of the smooth function.

(Forbes et al., 2018; Hobbs et al., 2009). For instance, many freshwater ecosystem restoration paradigms presume the trajectory of recovery will match the trajectory of decline, and the historical assemblages and process can be restored by incrementally reversing anthropogenic pressure (Schönach et al., 2018).

The Anthropocene baseline concept, defined based on whether return to the historical variability is feasible, can be categorized into two types (Kopf et al., 2015). The first type arises because of socioeconomic limitations on reducing anthropogenic pressures, which will prevent recovery to historical conditions (Fig. 6a). For instance, physically removal of all dams, restoration of river channels, and reduction in catchment nutrient loadings might altogether restore lake ecosystems. Socioeconomic constraints related to financial investment and social costs, however, such as food production and the livelihood of people in rural communities, might prevent the full restoration. The second type occurs when ecosystems have experienced state change or regime shift by crossing a catastrophic threshold (Fig. 6b). Under this circumstance, the ecological constraint and internal positive feedback mechanisms have prevented the full restoration even the pressures are reversed far enough to mimic the conditions that maintain the historical baseline(Kopf et al., 2015).

In the MLYB, researchers have observed extensive hydro-morphological, physical, chemical, and biological modification in many lakes over the past century (Wang, 2015). Defining the proper reference condition for lake restoration in the MLYB is not easy due to both socioeconomic limitations and ecological constraints. For instance, heavy metal pollution in lakes poses a great challenge for the health of lake ecosystems health due to their potential biological toxicity, environmental durability, and biological accumulation (Xu et al., 2017b; Yuan et al., 2014). The synthesis results from this study suggest that the heavy metal pollution in many lakes was relatively low before the 1950s, and then increased to a moderate level during the 1970s, and then increased significantly since the 1980s (Fig. 7a). Exogenous inputs from human activities and rapid economic developments (i.e. wastewater discharge, energy production) are the main sources of heavy metals in lake sediments (Xu et al., 2017b).

Though great effort has been made in recent decades, such as control pollution sources and implements strict enforcement of regulation and laws, the heavy metal concentration in many lake sediments still remains at very high level (Guo et al., 2015). Reducing the heavy metal concentration to pre-1950 might be an ideal target for lake restoration. However, financial, social and institutional limitations often constrained the full restoration, at least under prevailing political and economic conditions. Moreover, catchment soils with high levels of heavy metal concentration will bring more heavy metals into the lakes through rainfall and catchment erosion, even without new input from industries (Xu et al., 2017b). We suggest that the Anthropocene baseline of heavy metal pollutions for the studied lakes should be classified as type I baseline, and the levels of the 1960–1970 s might be a practical reference condition for restoration target for most of the lakes.

Another example is lake sediment accumulation rates, which have changed substantially owing to the large scale of river regulation, hydrological modification, and land use change (Xue et al., 2010). In the MLYB, many shallow lakes experience enhanced swamping and silting with increased sedimentation, reduced storage capacity, which poses a great threat to flood hazards and ecological and social security (Du et al., 2011). Though sedimentation rate varies significantly among different lakes due to site-specific characters, the general pattern shows that the sedimentation rates have increased significantly in recent decades for most lakes (Fig. 7b). Several lakes (Taihu, Dianshan, Xijiu, Chaohu, Shitang, and Donghu lakes) show extremely high sedimentation rates during the recent twenty years, whereas other lakes (Taibai, Liangzi, Zhangdu lakes) have relative moderate increase of sedimentation rate during the same period. Xu et al. (2017a) have suggested that pre-1900 could be used as the historical reference point for restoration. Geo-hydro-morphological or catchment characteristics of soils have irreversibly changed in the past century, however, especially during the period 1950 s–1980 s, when large scale of river regulation as well as dam and reservoir construction were carried out. We suggest that these severely degraded lakes with high sedimentation rate could be grouped into the type I Anthropocene baseline, and restoration to their 1970 s–1980 s level might be a realistic target. For other lakes with low or moderate levels can still be recovered to their pre-1900 condition if proper management action are taken.

Ecological constraints also complicate the restoration and management of the degraded lake ecosystem in the MLYB. Long-term paleo-ecological records reveal that rather than gradually declining, most studied lake ecosystems have undergone abrupt shift across different trophic levels during the past several decades (Fig. 3). Many lake ecosystems have exceeded their historical range of variability with the new configuration, and probably have transformed into novel ecosystems (Zhang et al., 2016). Moreover, as many lakes transition to turbid states, the positive feedback loops between sediment nutrient release, the alga community, and the loss of macrophyte could further prevent the restoration of these highly altered lake ecosystems (Scheffer and Jeppesen,

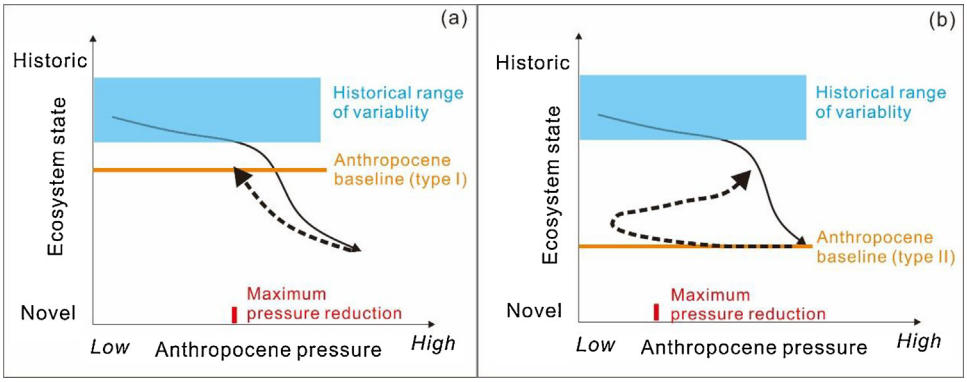


**Fig. 6.** Conceptual figure showing two types of the Anthropocene baseline for lake restoration (modified from Kopf et al., 2015). The black line represents the ecosystem degradation trajectory, while the black dash line represents the recovery trajectory. Anthropocene Baselines (brown lines) arise when the restoration potential is outside of the historical baseline (the blue box) range of variability. (a) Type I: Restoration to the historical range of variability is constrained by socioeconomic limitation on reducing anthropogenic drivers (maximum pressure reduction); (b) Type II: Ecosystem has undergone regime shift, which makes it impossible to return to their past configuration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

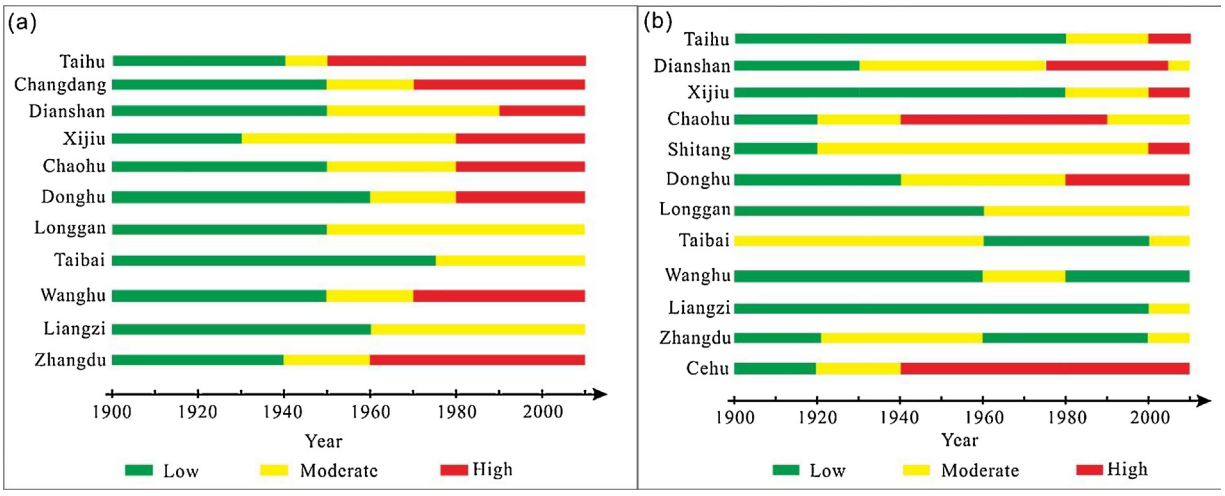


**Fig. 7.** Temporal patterns of heavy metal pollution (a) and sediment accumulation rate (SAR) (b) in lake sediment in the MLYB over the last one century. In each figure, green, yellow, and red colors represent the low, moderate, and high levels, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2007). For instance, monitoring date suggests that, while the nutrient level has been reduced in the Taihu lake since 2007, due to extensive management intervention, this lake still experience frequent cyanobacteria blooms and remain outside the historical range of variability (Xu et al., 2015). It should be noticed that the diagrams (Figs. 3 and 7) illustrated in this study are not as a precise target baseline for lake restoration, but rather as the starting point for understanding and define the realistic target for lake restoration. Investigating and defining the exact value of practical restoration target for different system components requires more detailed work.

## 4. Conclusion and management application

Under increasing anthropogenic pressure, either globally through climate change or more locally through overexploitation and biodiversity loss, abrupt and catastrophic changes in lake ecosystems will likely increase in strength and frequency. Lake scientists and managers in China and elsewhere are facing pressing challenges to manage highly altered lake ecosystems and keep them within the safe operating spaces. Using the Middle and Lower Yangtze River Basin as an example, this paper has shown that pronounced multi-decadal variability and abrupt change in many shallow lakes over the past century were driven by multiple accumulating drivers. Most of the studied lakes have exceeded their historical variability, and are not easy to restore to their historical reference condition (or pristine condition) either due to socioeconomic or ecological constraints.

Sustainable management of lake ecosystem will require a conceptual shift away from the current emphasis on protection or restoration of stable lake ecosystem at equilibrium, to a reality in which ecosystem is more dynamic and complex. Lake scientists, managers, and policymakers in the MLYB should critically evaluate whether lake ecosystems have approached to an Anthropocene baseline that is difficult to return to the historical conditions (Kopf et al., 2015), and adjust intervention approaches accordingly. We suggest that it is crucial to identify lakes that have not yet shifted and prioritize the implementation of new management intervention that could stabilize /restore the system to an appropriate historical level. Meanwhile, accepting the likelihood that some lakes have changed permanently to a different state, which should be seen as a reality and avoid unnecessary restoration practices that are not feasible and affordable. The priority of managing these lakes that have shifted is to avoid the new states degrading to an even more degraded and resilient state. Policies and management strategies based on static approaches are outdated and insufficient. Embracing this paradigm shift will necessitate a transformation in the governance and management of this highly altered lake ecosystem in the MLYB region, which may also serve as an example for other lake ecosystems around the world.

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## References

Baig, S.A., Huang, L.L., Sheng, T.T., Lv, X.S., Yang, Z., Qasim, M., Xu, X.H., 2017. Impact of climate factors on cyanobacterial dynamics and their interactions with water quality in South Taihu Lake, China. Chem. Ecol. 33, 76–87.

Battarbee, R.W., Bennion, H., 2011. Palaeolimnology and its developing role in assessing the history and extent of human impact on lake ecosystems. J. Paleolimnol. 45, 399–404.

Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., Juggins, S., 2001. Diatoms. Tracking Environmental Change Using Lake Sediments, vol. 3. , pp. 155–202.

Beklioğlu, M., Meerhoff, M., Davidson, T.A., Ger, K.A., Havens, K., Moss, B., 2016. Preface: shallow lakes in a fast changing world. Hydrobiologia 778, 9–11.

Cai, C.F., Gu, X.H., Ye, Y.T., Yang, C.G., Dai, X.Y., Chen, D.X., Yang, C., 2013. Assessment of pollutant loads discharged from aquaculture ponds around Taihu Lake, China. Aquac. Res. 44, 795–806.

Cao, L., Zhao, P., Yan, Z., Jones, P., Zhu, Y., Yu, Y., Tang, G., 2013. Instrumental temperature series in eastern and central China back to the nineteenth century. J. Geophys. Res. Atmos. 118, 8197–8207.

Capon, S.J., Lynch, A.J.J., Bond, N., Chessman, B.C., Davis, J., Davidson, N., Finlayson, M., Gell, P.A., Hohnberg, D., Humphrey, C., Kingsford, R.T., Nielsen, D., Thomson, J.R., Ward, K., Nally, R.M., 2015. Regime shifts, thresholds and multiple stable states in freshwater ecosystems; a critical appraisal of the evidence. Sci. Total Environ..

Chen, X., Yang, X., Dong, X., Liu, Q., 2011. Nutrient dynamics linked to hydrological condition and anthropogenic nutrient loading in Chaohu Lake (southeast China). Hydrobiologia 661, 223–234.

Collins, S.L., Carpenter, S.R., Swinton, S.M., Orenstein, D.E., Childers, D.L., Gragson, T. L., Grimm, N.B., Grove, J.M., Harlan, S.L., Kaye, J.P., Knapp, A.K., Kofinas, G.P., Magnuson, J.J., McDowell, W.H., Melack, J.M., Ogden, L.A., Robertson, G.P., Smith, M.D., Whitmer, A.C., 2011. An integrated conceptual framework for long-term social–ecological research. Front. Ecol. Environ. 9, 351–357.

Conversi, A., Dakos, V., Gårdmark, A., Ling, S., Folke, C., Mumby, P.J., Greene, C., Edwards, M., Blenckner, T., Casini, M., Pershing, A., Möllmann, C., 2015. A holistic view of marine regime shifts. Philos. Trans. R. Soc. B: Biol. Sci. 370, 1–8.
Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., Carstensen, J., Cole, M.J., Cornell, S.E., Dawson, T.P., Doncaster, C.P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A.W., Nykvist, B., Poppy, G.M., 2014. Safe and just operating spaces for regional social-ecological systems. Glob. Environ. Chang. Part A 28, 227–238.
Deng, H., Liu, C., Lu, Y., He, D., Tian, H., 2017. Changes in record-breaking temperature events in China and projections for the future. Theor. Appl. Climatol. 1–12.
Ding, J., Cao, J., Xu, Q., Xi, B., Su, J., Gao, R., Huo, S., Liu, H., 2015. Spatial heterogeneity of lake eutrophication caused by physiogeographic conditions: an analysis of 143 lakes in China. J. Environ. Sci. 30, 140–147.
Dong, X., Bennion, H., Battarbee, R., Yang, X., Yang, H., Liu, E., 2008. Tracking eutrophication in Taihu Lake using the diatom record: potential and problems. J. Paleolimnol. 40, 413–429.
Dong, X., Yang, X., Chen, X., Liu, Q., Yao, M., Wang, R., Xu, M., 2016. Using sedimentary diatoms to identify reference conditions and historical variability in shallow lake ecosystems in the Yangtze floodplain. Mar. Freshw. Res. 67, 803–815.
Du, C.C., Liu, E.F., Yang, X.D., Wu, Y.H., Xue, B., 2012. Characteristics of enrichment and evaluation of anthropogenic pollution of heavy metals in the sediments of Lake Chaohu. J. Lake Sci. 24, 59–66.
Du, Y., Xue, H.P., Wu, S.J., Ling, F., Xiao, F., Wei, X.H., 2011. Lake area changes in the middle Yangtze region of China over the 20th century. J. Environ. Manage. 92, 1248–1255.
Dubois, N., Saulnier-Talbot, É., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R., Gomes, D.F., Gregory-Eaves, I., Humane, S., Kattel, G., Jenny, J., Langdon, P., Massaferro, J., McGowan, S., Mikomägi, A., Ngoc, N.T.M., Ratnayake, A.S., Reid, M., Rose, N., Saros, J., Schillereff, D., Tolotti, M., Valero-Garcés, B., 2017. First human impacts and responses of aquatic systems: a review of palaeolimnological records from around the world. Anthr. Rev. 0, 2053019617740365.
Ellis, E.C., Wang, S.M., 1997. Sustainable traditional agriculture in the Tai Lake Region of China. Agric. Ecosyst. Environ. 61, 177–193.
Fægri, K., Iversen, J., 1989. A textbook of pollen analysis. J. Biogeogr. IV, 328.
Fang, J., Wang, Z., Zhao, S., Li, Y., Tang, Z., Yu, D., Ni, L., Liu, H., Xie, P., Da, L., Li, Z., Zheng, C., 2006. Biodiversity changes in the lakes of the Central Yangtze. Front. Ecol. Environ. 4, 369–377.
Fisheries Bureau of Ministry of Agriculture, 2017. China Fishery Statistical Yearbook. China Agriculture Press, Beijing.
Folt, C.L., Chen, C.Y., Moore, M.V., Burnaford, J., 1999. Synergism and antagonism among multiple stressors. Limnol. Oceanogr. 44, 864–877.
Forbes, C.J., Gillson, L., Hoffman, M.T., 2018. Shifting baselines in a changing world: identifying management targets in endangered heathlands of the Cape Floristic Region, South Africa. Anthropocene 22, 81–93.
Ge, Y., Zhang, K., Yang, X., 2018. Long-term succession of aquatic plants reconstructed from palynological records in a shallow freshwater lake. Sci. Total Environ. 643, 312–323.
Guo, W., Huo, S., Xi, B., Zhang, J., Wu, F., 2015. Heavy metal contamination in sediments from typical lakes in the five geographic regions of China: distribution, bioavailability, and risk. Ecol. Eng. 81, 243–255.
Hicks, C.C., Crowder, L.B., Graham, N.A.J., Kittinger, J.N., Le Cornu, E., 2016. Social drivers forewarn of marine regime shifts. Front. Ecol. Environ. 14, 252–260.
Hilt, S., Brothers, S., Jeppesen, E., Veraart, A.J., Kosten, S., 2017. Translating regime shifts in shallow lakes into changes in ecosystem functions and services. BioScience 67, 928–936.
Hobbs, R.J., Higgs, E., Harris, J.A., 2009. Novel ecosystems: implications for conservation and restoration. Trends Ecol. Evol. 24, 599–605.
Hughes, T.P., Linares, C., Dakos, V., van de Leemput, I.A., van Nes, E.H., 2013. Living dangerously on borrowed time during slow, unrecognized regime shifts. Trends Ecol. Evol. 28, 149–155.
Jeppesen, E., Meerhoff, M., Davidson, T.A., Trolle, D., Sondergaard, M., Lauridsen, T.L., Beklioglu, M., Brucet, S., Volta, P., Gonzalez-Bergonzoni, I., Nielsen, A., 2014. Climate change impacts on lakes: an integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes. J. Limnol. 73, 88–111.
Jian, L., Storch, H., Xing, C., Zorita, E., Zheng, J., Wang, S., 2005. Simulated and reconstructed winter temperature in the eastern China during the last millennium. Sci. Bull. 50, 2872–2877.
Johnson, C.N., Balmford, A., Brook, B.W., Buettel, J.C., Galetti, M., Guangchun, L., Wilmshurst, J.M., 2017. Biodiversity losses and conservation responses in the Anthropocene. Science 356, 270–275.
Kattel, G.R., Dong, X., Yang, X., 2016. A century-scale, human-induced ecohydrological evolution of wetlands of two large river basins in Australia (Murray) and China (Yangtze). Hydrol. Earth Syst. Sci. 20, 2151–2168.
Kong, X., He, Q., Yang, B., He, W., Xu, F., Janssen, A.B., Kuiper, J.J., van Gerven, L.P., Qin, N., Jiang, Y., Liu, W., Yang, C., Bai, Z., Zhang, M., Kong, F., Janse, J.H., Mooij, W.M., 2016. Hydrological regulation drives regime shifts: evidence from paleolimnology and ecosystem modeling of a large shallow Chinese lake. Glob. Chang. Biol..
Kopf, R.K., Finlayson, C.M., Humphries, P., Sims, N.C., Hladyz, S., 2015. Anthropocene baselines: assessing change and managing biodiversity in human-dominated aquatic ecosystems. BioScience 65, 798–811.
Le, C., Zha, Y., Li, Y., Sun, D., Lu, H., Yin, B., 2010. Eutrophication of lake waters in China: cost, causes, and control. Environ. Manage. 45, 662.
Li, H., Loyalka, P., Rozelle, S., Wu, B., 2017. Human capital and China's future growth. J. Econ. Perspect. 31, 25–48.
Li, H.B., Shen, Y., Li, G.L., Hong, D., Bo, X., Jing, D., Gao, J.B., Hong, Y.W., Wong, M.H., 2013. Spatial distribution and historical records of mercury sedimentation in urban lakes under urbanization impacts. Sci. Total Environ. 445–446, 117–125.
Liu, Q., Yang, X., Anderson, N.J., Liu, E., Dong, X., 2012. Diatom ecological response to altered hydrological forcing of a shallow lake on the Yangtze floodplain, SE China. Ecohydrology 5, 316–325.
Meng, J.Y.C., X, M., 1993. Jintan County Annals. Jiangsu People's Publishing, Jiangsu, China.
Miao, L., Zhu, F., Sun, Z., Moore, J.C., Cui, X., 2016. China's land-use changes during the past 300 years: a historical perspective. Int. J. Environ. Res. Public Health 13, 847.
Möllmann, C., Folke, C., Edwards, M., Conversi, A., 2015. Marine regime shifts around the globe: theory, drivers and impacts. Philos. Trans. Biol. Sci. 370, 1–5.
O'Gorman, E.J., Emmerson, M.C., 2009. Perturbations to trophic interactions and the stability of complex food webs. Proceedings of the National Academy of Sciences of the United States of America 106, 13393–13398.
Qin, B., Gao, G., Zhu, G., Zhang, Y., Song, Y., Tang, X., Xu, H., Deng, J., 2013. Lake eutrophication and its ecosystem response. Chinese Sci. Bull. 58, 961–970.
Scheffer, M., Barrett, S., Carpenter, S.R., Folke, C., Green, A.J., Holmgren, M., Hughes, T. P., Kosten, S., Van De Leemput, I.A., Nepstad, D.C., Van Nes, E.H., Peeters, E.T.H.M., Walker, B., 2015. Creating a safe operating space for iconic ecosystems: manage local stressors to promote resilience to global change. Science 347, 1317–1319.
Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.
Scheffer, M., Carpenter, S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol. Evol. 18, 648–656.
Scheffer, M., Jeppesen, E., 2007. Regime shifts in shallow lakes. Ecosystems 10, 1–3.
Schönach, P., Nygrén, N.A., Tammeorg, O., Heikkinen, M., Holmroos, H., Massa, I., Niemistö, J., Tapio, P., Horppila, J., 2018. The past, present, and future of a lake: interdisciplinary analysis of long-term lake restoration. Environ. Sci. Policy 81, 95–103.
Seddon, A.W.R., Froyd, C.A., Witkowski, A., Willis, K.J., 2014. A quantitative framework for analysis of regime shifts in a Galápagos coastal lagoon. Ecology 95, 3046–3055.
Shen, J., Liu, E., Zhu, Y., Hu, S., Qu, W., 2007. Distribution and chemical fractionation of heavy metals in recent sediments from Lake Taihu. China. Hydrobiologia 581, 141–150.
Shi, X.L., Qin, B.Q., 2013. Environmental evolution of Wanghu Lake in the middle Yangtze River and its responses to human activities. Geogr. Res. 32, 808–816.
Simpsona, G.L., Anderson, N.J., 2009. Deciphering the effect of climate change and separating the influence of confounding factors in sediment core records using additive models. Limnol. Oceanogr. 54, 2529–2541.
Spears, B.M., Futter, M.N., Jeppesen, E., Huser, B.J., Ives, S., Davidson, T.A., Adrian, R., Angeler, D.G., Burthe, S.J., Carvalho, L., Daunt, F., Gsell, A.S., Hessen, D.O., Janssen, A.B.G., Mackay, E.B., May, L., Moorhouse, H., Olsen, S., Sondergaard, M., Woods, H., Thackeray, S.J., 2017. Ecological resilience in lakes and the conjunction fallacy. Nat. Ecol. Evol. 1, 1616–1624.
Szeroczyńska, K.S.-K., 2007. Atlas of Subfossil Cladocera from Central and Northern Europe. Tow Przyj Dolnej Wisły, Świecie.
Wang, J., Sheng, Y., Tong, T.S.D., 2014. Monitoring decadal lake dynamics across the Yangtze Basin downstream of Three Gorges Dam. Remote Sens. Environ. 152, 251–269.
Wang, S.M.D., H.S, 1998. Lakes of China. Science Press, Beijing.
Wang, S.R., 2015. Lake Environment Evolution and Protection Management. Science Press, Beijing.
Wang, S.R., Meng, W., Jin, X.C., Zheng, B.H., Zhang, L., Xi, H.Y., 2015. Ecological security problems of the major key lakes in China. Environ. Earth Sci. 74, 3825–3837.
Wu, Y., Liu, E., Yao, S., Zhu, Y., Xia, W., 2010a. Recent heavy metal accumulation in Dongjiu and Xijiu lakes, East China. J. Paleolimnol. 43, 385–392.
Wu, Y.H., Liu, E.F., Bing, H.J., Yang, X.D., Xue, B., Xia, W.L., 2010b. Geochronology of recent lake sediments from Longgan Lake, middle reach of the Yangtze River, influenced by disturbance of human activities. Sci. China Earth Sci. 53, 1188–1194.
Xu, D., Cai, Y., Wu, X., Jiang, H., Leng, X., An, S., 2015. Regime shifts and resilience of the lake taihu social-ecological system under long-term external disturbance (1960s-2000s). Clean - Soil, Air, Water 43, 561–568.
Xu, M., Dong, X., Yang, X., Chen, X., Zhang, Q., Liu, Q., Wang, R., Yao, M., Davidson, T.A., Jeppesen, E., 2017a. Recent sedimentation rates of shallow lakes in the middle and lower reaches of the Yangtze River: patterns, controlling factors and implications for lake management. Water 2017.
Xu, Y.F., Wu, Y., Han, J.G., Li, P.P., 2017b. The current status of heavy metal in lake sediments from China: pollution and ecological risk assessment. Ecol. Evol. 7, 5454–5466.
Xue, B., Yao, S., Xia, W., Zhu, Y., 2010. Some sediment-geochemical evidence for the recent environmental changes of the lakes from the middle and lower Yangtze River basin. China. Quat. Int. 226, 29–37.
Yang, H., Yi, C., Xie, P., Xing, Y., Ni, L., 2005. Sedimentation rates, nitrogen and phosphorus retentions in the largest urban Lake Donghu, China. . Radioanalyt. Nuclear Chem. 267, 205–208.
Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011. 50,000 dams later: erosion of the Yangtze River and its delta. Glob. Planet. Change 75, 14–20.
Yang, X., Anderson, N.J., Dong, X., Shen, J.I., 2008. Surface sediment diatom assemblages and epilimnetic total phosphorus in large, shallow lakes of the Yangtze floodplain: their relationships and implications for assessing long-term eutrophication. Freshw. Biol. 53, 1273–1290.

Yang, X., Lu, X., 2014. Drastic change in China's lakes and reservoirs over the past decades. Sci. Rep. 4, 6041.
Yuan, F., Depew, R., Soltis-Muth, C., 2014. Ecosystem regime change inferred from the distribution of trace metals in Lake Erie sediments. Sci. Rep. 4, 7265.
Zeng, L., McGowan, S., Cao, Y., Chen, X., 2018. Effects of dam construction and increasing pollutants on the ecohydrological evolution of a shallow freshwater lake in the Yangtze floodplain. Sci. Total Environ. 621, 219–227.
Zhang, E., Cao, Y., Langdon, P., Jones, R., Yang, X., Shen, J., 2012. Alternate trajectories in historic trophic change from two lakes in the same catchment, Huayang Basin, middle reach of Yangtze River. China. J. Paleolimnol. 48, 367–381.
Zhang, E., Liu, E., Jones, R., Langdon, P., Yang, X., Shen, J., 2010. A 150-year record of recent changes in human activity and eutrophication of Lake Wushan from the middle reach of the Yangze River, China. J. Limnol. 69, 235–241.
Zhang, K., Dearing, J.A., Tong, S.L., Hughes, T.P., 2016. China's degraded environment enters a new normal. Trends Ecol. Evol. 31, 175.
Zhang, Q., Dong, X., Yao, M., Chen, S., Yang, X., 2013. Environmental changes in response to altered hydrological connectivities with the Yangtze River in Lake Zhangdu(Hubei Province) over the past 200 years. J. Lake Sci. 25, 463–470.
Zhao, Y., Wang, R., Yang, X., Dong, X., Xu, M., 2016. Regime shifts revealed by paleoecological records in Lake Taibai's ecosystem in the middle and lower Yangtze River Basin during the last century. J. Lake Sci. 28, 1381–1390.
Zhou, Y.Q., Ma, J.R., Zhang, Y.L., Qin, B.Q., Jeppesen, E., Shi, K., Brookes, J.D., Spencer, R. G.M., Zhu, G.W., Gao, G., 2017. Improving water quality in China: environmental investment pays dividends. Water Res. 118, 152–159.
Zhu, M., Paerl, H.W., Zhu, G., Wu, T., Li, W., Shi, K., Zhao, L., Zhang, Y., Qin, B., Caruso, A.M., 2014. The role of tropical cyclones in stimulating cyanobacterial (Microcystis spp.) blooms in hypertrophic Lake Taihu, China. Harmful Algae 39, 310–321.